Can MPI Be Used for Persistent Parallel Services?

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Abstract. MPI is routinely used for writing parallel applications, but it is not commonly used for writing long-running parallel services, such as parallel file systems or job schedulers. Nonetheless, MPI does have many features that are potentially useful for writing such software. In this paper, we use the PVFS2 parallel file system as a motivating example to study the needs of software that provide persistent parallel services and evaluate whether MPI is a good match for those needs. We also ran experiments to determine the gaps between what the MPI Standard enables and what MPI implementations currently support. The results of our study indicate that MPI can enable persistent parallel systems to be developed with less effort and also provide high performance, but MPI implementations will need to provide better support for certain features. We also describe an area where additions to the MPI Standard would be useful.

1 Introduction

Achieving good performance on today's high-end computing machines involves effectively utilizing a variety of network interconnects, a large number of compute resources, and quality algorithms. Application developers make heavy use of libraries and tools to manage this complexity while still delivering high performance. Parallel application writers commonly choose the message-passing model, embodied by the MPI Standard [10], for their work. The MPI Standard defines a rich API that can be used across many disparate hardware platforms and provides many useful features such as datatype packing, collective communication, nonblocking communication, and dynamic process management, while quality MPI implementations provide heterogeneous communication and deliver high performance.

Parallel system services, on the other hand, are usually not written in MPI. One would imagine, however, that MPI's portability, performance, and features should make it an attractive candidate for implementing parallel system services as well. If so, why don't these software use MPI? Could they? We investigate these issues in detail in this paper. For concreteness, we use the parallel file system PVFS2 [1] as an example for studying the needs of such software. We

have been heavily involved in the development of PVFS2 and are very familiar with its requirements. PVFS2 and its predecessor, PVFS [3], represent a decade of parallel file system research and engineering. PVFS2 was written to deliver high performance at scales of hundreds of servers and tens of thousands of clients and has done so on some of the worlds fastest and largest supercomputers, such as IBM BG/L, Cray XT-3, and large Linux clusters.

We first give a brief overview of PVFS2 and its architecture. Then, using PVFS2 as an example, we study the needs of software for persistent parallel services and examine how well MPI is equipped to meet those needs. We find in most cases that the MPI Standard supports the features we need, but some of them are not commonly supported in all MPI implementations. We also describe an area where we would benefit from additions to the MPI Standard.

2 PVFS2: A Persistent Parallel Service

A *Persistent Parallel Service* (PPS) is system software that manages multiple hardware components to provide a single logical resource for use by parallel applications. It is persistent in the sense that it exists beyond the life of a single application. A parallel file system is an example of a persistent parallel service.

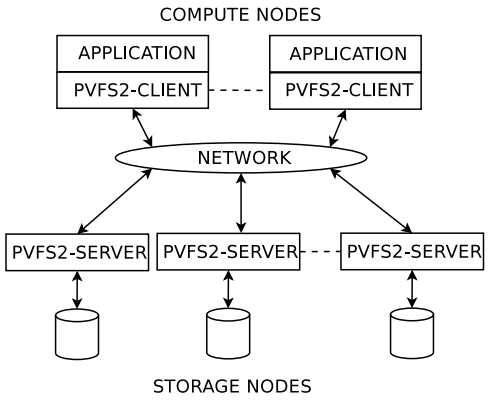


Fig. 1. *PVFS2 architecture.* `pvfs2-client` *forwards kernel-level requests to* `pvfs2-server` *processes running on the servers.* `pvfs2-server`*, in turn, deals with managing data on storage devices.*

PVFS2 [1] is a high-performance parallel file system being developed as a joint project between Argonne National Laboratory, Clemson University, and the Ohio Supercomputer Center. PVFS2 comprises multiple servers, which are persistent. A PVFS2 file is striped across these servers. PVFS2 software on the client side hides all these details from the client and instead presents a single logical view of a file. File striping across multiple servers enables multiple clients to access different parts of a file in parallel, resulting in high performance.

PVFS2 provides many features such as native support for several popular networking technologies like Myrinet, InfiniBand, and TCP/IP, multiple APIs (POSIX, MPI-IO), user-controlled striping of files across nodes, a well defined interface for defining new data distribution schemes, support for heterogeneous clusters, and distributed metadata. It uses commodity network and storage hardware and is easy to install (no kernel patch). The familiar UNIX file tools (such as ls, cp, and rm) can be used on PVFS2 files and directories.

In the following sections, we use PVFS2 as an example to study the common needs of persistent parallel services and then investigate how well MPI supports those features.

3 Service Identification

Any persistent service needs to handle the important issue of locating the servers. For traditional network services, the IP address and port number are often listed in a configuration file. PVFS2 follows a similar approach. PVFS2 has two types of configuration files: for the servers and for the clients. The configuration files for PVFS2 servers list all the servers that form the parallel file system. Each server reads this list at startup. A PVFS2 client uses its own configuration file to locate PVFS2 servers (see Figure 2). This file resembles a Unix `/etc/fstab` file and provides the network address of any one of the PVFS2 servers, a mount point on the client system, and a few other parameters. The client enquires with the listed server about the file system, obtains a complete listing of all the servers, and then begins interacting with the file system.

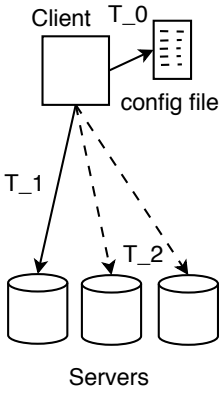


Fig. 2. *Client establishing connections to PVFS2 servers, current method. The client has to look at a configuration file and connect to one of the PVFS2 servers before it knows where the other PVFS2 servers are.*

If PVFS2 used MPI, it could use MPI's features that enable service identification. The MPI name publishing interface (`MPI_Publish_name`, `MPI_Lookup_name`) provides a method for clients and servers to exchange information. Clients could use a well-known key to discover an initial contact point. This well-known key would provide service discovery that is independent of the underlying network interconnect or even MPI implementation. Clients would be insulated from server changes, be it a different port, host, or even interconnect, without system administrators needing to update client-side configuration files.

In practice, however, MPI implementations currently do not support this functionality as well as needed. For this functionality to be usable, MPI implementations must support name publishing and resolution across independently started MPI processes because PVFS2 servers are not restarted with every new client application. We ran some tests with several commonly deployed MPI implementations and found that they do not support this mode of operation (as summarized in Table 1). These MPI implementations do let us exchange information between independent processes via the name-publishing interface, but with certain restrictions. For example, the processes must be part of the same MPD ring in MPICH2 [11], and some other restrictions with the `orted` daemons in Open MPI [12]. This additional component (MPD or orted) must also be persistent and able to tolerate node failure.

Table 1. *Capabilities of MPI implementations. An ideal implementation would have a Y in all rows.*

	Implementation		
	MPICH2	Open MPI	BGL-MPI
Feature	1.0.3	1.0.1	V1R2M1
Published name appears to other singleton processes	N	N	N
Connect/Accept work under singleton MPI_Init	Y*	N	N
MPI_Comm_join works under singleton MPI_Init	Y*	N	N
Requires a previously established MPI environment (lamboot, MPD, others)	N*	Y	Y
MPI_Comm_spawn works under singleton MPI_Init	?	?	?
MPI datatype processing supports heterogeneous architectures	N	N	?
Support for `external32`	N	N	N

4 Establishing Connection

After clients have discovered what services are running, they need to connect to those services. The traditional Unix socket model has the familiar TCP `accept/connect` handshake. Other protocols have analogous mechanisms. PVFS2 uses an abstraction that is layered on top of the connection mechanisms of multiple networks, providing portability.

The use of MPI could simplify this process greatly. MPI's dynamic process functionality supports two different ways for clients to establish communication with servers. One approach has the server process call `MPI_Comm_accept`, waiting for a corresponding client-side call to `MPI_Comm_connect`. `MPI_Comm_join` provides another approach for two processes that already share a UNIX network socket to establish MPI communication. In both cases, the functions returns an MPI intercommunicator, over which the clients and servers can communicate. Furthermore, the accept/connect functions in MPI are *collective*. A group of clients can connect to a group of servers at the same time, and the resulting intercommunicator can be used for communication between any client and any server.

These MPI functions are much easier to use than the corresponding Unix socket ones. In addition, they are portable. The MPI implementation takes care of implementing the connection mechanism over the underlying network protocol, freeing the system software developer from the effort.

Client connections done with MPI do come with a few challenges. The accept/connect approach needs the name of an open MPI port. If the name-publishing interface in an MPI implementation works across independently launched MPI programs (as described in Section 3), `MPI_Publish_name` and `MPI_Lookup_name` can greatly simplify the process of obtaining the MPI port name. Otherwise, unwieldy implementation-specific strings would have to be passed around by hand. `MPI_Comm_join` does not have a dependency on the name-publishing interface.

It does, however, require a UNIX network socket to be already set up between the client and server. The socket is used only for the initial handshake; all other communication goes over the native transport used by the MPI implementation.

5 Fast Data Transfer

A persistent parallel service needs fast data transfer between clients and servers. PVFS2 has a few specific needs in this area.

- It needs fast communication of data between clients and servers over a number of different networking technologies, using the fastest protocol for each network, for example TCP over Ethernet, GM or MX over Myrinet, the native InfiniBand protocol over InfiniBand.
- For control messages between client and server (not for data), it needs support for heterogeneity, because clients and servers could run on different architectures. For example, Argonne's IBM BG/L system has a mix of PPC64, PPC32, and IA32 nodes.
- It needs support for communicating noncontiguous data efficiently.
- It needs support for nonblocking communication.

A substantial amount of code has been written in PVFS2 to support these needs. PVFS2 uses an abstraction called the Buffered Message Interface (BMI) [4] for portable high-performance communication over multiple networks. For control messages, PVFS2 defines an encoding scheme that converts all commands to a fixed-length, little-endian format, which allows PVFS2 clients and servers to have any mix of byte endianess or word size. (Defining this encoding correctly took many iterations.) PVFS2 implements its own way of communicating noncontiguous data, which required several thousand lines of code.

MPI is a perfect fit for all these requirements. MPI provides a portable interface for communication, and MPI implementations do the job of implementing that interface efficiently on the underlying network. The MPI Standard supports heterogeneous communication through the use of MPI datatypes. MPI implementations, however, vary in their support for heterogeneity. For example, MPICH-1 does support heterogeneity, whereas MPICH-2 and Open MPI at present do not. The MPI Standard does have some limitations in that there is no universal way to express certain sized types, such as 64-bit integers, and PVFS2 file handles are 64-bit values. Nonetheless, we could use `MPI_LONG_LONG`, which is often 64 bit, or if not, use two `MPI_INT` types. MPI also supports communication of noncontiguous data through derived datatypes. MPI implementations, however, have historically not performed well on derived datatypes. Nonetheless, various research efforts have demonstrated that derived datatypes can be implemented in a way that delivers good performance [13, 15]. We hope MPI implementations will devote effort to optimizing derived datatypes. MPI also supports nonblocking communication, which allows us to overlap communication with disk I/O.

These features of MPI make it ideally suited for use in data communication, although better support is needed from implementations.

6 Fault Tolerance

Any persistent parallel software needs to be resilient against faults as far as possible. The robustness depends on how well the software itself is designed and implemented also also on the robustness of the external components that the software uses.

In a cluster environment, each PVFS2 server represents a potential point of failure, and error recovery becomes an important consideration. To that end, PVFS2 servers operate in a stateless manner: there are no locks to revoke or leases to offer, and client tracking is not necessary. This stateless nature makes recovering from server failure much easier. PVFS2 can retry operations in order to hide transient problems. If a server failure occurs, PVFS2 operations will time out and return an error to the caller. If a server has been restarted (either by hand or perhaps by a failover script) the newly restarted server will be able to service the client request.

If PVFS2 were implemented using MPI, it would require the MPI implementation to be resilient against failure. The MPI Standard itself does not say much about fault tolerance; it is left as a quality of the implementation. But MPI does have some features that can help in writing resilient programs. For example, MPI has a very well-defined mechanism of error returns from functions, and users can specify their own error handlers. The default error handler is that the entire job aborts on error, but users can change that to "errors return" or define their own error handler. MPI also has the notion of intercommunicators for two groups of processes (for example, clients and servers) to communicate. When two independently started processes connect to each other and communicate over the intercommunicator, the failure of one process need not cause the other process to die.

Most MPI implementations, however, are not robust against errors. For example, if the connection between two processes is lost, the entire MPI job may abort; or if a single process is killed, the entire MPI job may get killed. This kind of failure will not be good for a parallel file system that uses MPI. Although there are some efforts at building fault-tolerant MPI implementations [2, 7], more work is needed in this area.

Another area where MPI can help is in the parity calculation for a software-RAID like approach in providing fault-tolerance for data stored on the parallel file system. Gropp et al. proposed a *lazy redundancy* scheme in [8] which makes use of both MPI-IO consistency semantics and the MPI collective functions `MPI_Reduce_scatter` and `MPI_Reduce`. Implementing this scheme becomes much easier when PVFS2 servers are based on MPI.

The processes providing the parallel service can only communicate with each other once they have established an MPI communicator. On one extreme we could establish many two-process communicators. Having all these communicators makes the system resilient to failure, but greatly complicates any all-to-all or one-to-many messaging algorithms. At the other extreme we could establish an all-encompassing communicator spanning all processes. In exchange for simplified communication, such a system would be more fragile. We would need some

way to re-form this communicator when one of the member processes died, while still maintaining the properties of MPI communicators (context, fixed identifiers) that make them so useful.

7 Collective and Aggregate Operations

In PVFS2, many operations require multiple steps performed across many servers. Creating a new file requires a single metadata entry and a data file entry on each server. Removing a file requires removal of the data file from each server followed by removal of the corresponding metadata entry. A `stat` system call needs to collect partial file size information from each server before returning the total size of a file. While the client code makes just one function call for these operations, the underlying library carries out a one-to-many operation. The client library posts these messages as nonblocking sends to the servers and waits for their response.

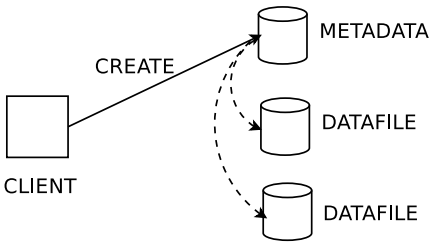
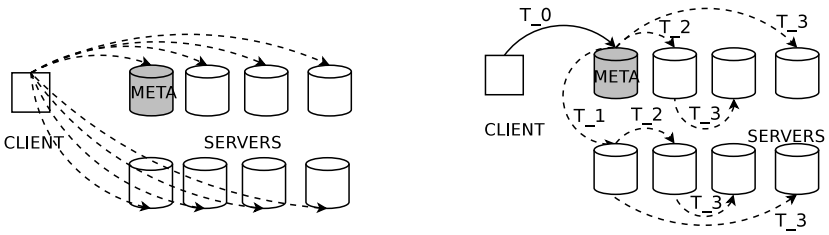


Fig. 3. *An aggregate operation lets a single* `create` *request initiate 1: creation of the metadata entry 2: datafile entries on each server. The servers could potentially be better connected to each other than clients (as in a WAN), yielding fewer messages, better performance and lower latency*

An alternate approach would have clients send a single "create file" message to one of the servers and have server then orchestrate actions on the client's behalf, as described in [5]. This approach simplifies the synchronization of operations and leads to the natural use of structured communication patterns such as broadcasting an operation request using a tree-based algorithm as shown in Figure 4(b).

Aggregate operations also make deployment over the wide-area more efficient. We can easily imagine a topology where the servers are located very near to each other while the clients may be quite far away, network-wise. These aggregate messages mean fewer network round trips and lower latency. The servers can exchange messages with each other over their local network and send a single response over the long-haul, high-latency link.

MPI is well known for its collective operations, such as broadcast, allreduce, and scatter/gather. Many implementations have optimized collective operations [14]. The collective communication operations in MPI are defined to be collective over a communicator; all processes in the communicator must call them. In an application, this requirement is easy to meet. In PVFS2, however, the servers do not know which client will issue the collective operation; for example, which client will want to delete a file. PVFS2 needs to be able to respond to unpredictable client requests. Therefore, the servers must either post nonblocking



(a) Independent file removal, 8 timesteps

(b) Collective file removal. 3 timesteps

Fig. 4. *File removal requires deletion of the data file on each server. The independent approach has very little room for optimization, requires careful coordination to keep metadata consistent, and $O(N)$ timesteps to complete. The collective approach simplifies metadata updates and requires only $O(log(N))$ timesteps.*

collective calls or a broadcast with a "wildcard" root that will be specified later. This functionality, however, doesn't exist in MPI; MPI collectives are blocking calls. There was a proposal for nonblocking collectives in the MPI-2 Forum, but it was not accepted. Some implementations have extensions that support this feature, for example, in IBM's MPI [9] (although it has been deprecated).

We are investigating the issue of how nonblocking (or wildcard) collectives could be supported as an extension to MPI and what their semantics would be. We plan to develop a prototype implementation.

8 Conclusions

Writing parallel system software can be a significant undertaking. A production parallel file system such as GPFS, GFS, Lustre, or PVFS2 takes many years to develop and stabilize. Much of this effort goes into implementing many of the features that MPI already supports, and this duplicate effort be avoided. While there are some challenges in implementing system software using MPI today, they are mainly due to the limitations of MPI implementations rather than deficiencies in the MPI Standard. At the same time, the addition of nonblocking collectives to MPI would make it even more useful for building parallel systems software.

The requirements we have discussed apply to more than just PVFS2 or other parallel file systems. For example, job schedulers could use MPI dynamic process functions to launch parallel jobs (`via MPI_Comm_spawn`), and system monitoring daemons could use MPI datatypes and support for heterogeneous communication to monitor disparate resources. Desai et al. in [6] used MPI to implement a variety of system-level application utilities, such as file staging, file synchronization, and a parallel shell.

We note that using MPI for implementing persistent system services does not restrict user applications to being MPI applications. The PVFS2 client can determine whether MPI has been initialized (by calling `MPI_Initialized`) and then call `MPI_Init` if it hasn't been. Clients and servers can then communicate using MPI. (Again, all implementations need to support this feature of MPI, called "singleton init.")

In summary, we would like to implement PVFS2 using MPI. We hope MPI implementers will take up the challenge and develop high-quality implementations that can be used to develop system software such as a parallel file system!

Acknowledgments

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